

Gravitational Waves, Gamma Ray Bursts, and Black Stars*

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Stars that are collapsing toward forming a black hole but appear frozen near their Schwarzschild horizon are termed “black stars”. The collision of two black stars leads to gravitational radiation during the merging phase followed by a delayed gamma ray burst during coalescence. The recent observation of gravitational waves by LIGO, followed by a possible gamma ray counterpart by Fermi, suggests that the source may have been a merger of two black stars with profound implications for quantum gravity and the nature of black holes.

From an asymptotic observer’s viewpoint, a collapsing body is forever suspended just above its Schwarzschild radius. The strong gravitational redshift near the surface of the collapsing body causes the body to appear black. Such objects are known as “frozen stars” or “black stars”. Black *holes* are the infinite time limit of black stars and traditionally black stars are viewed as indistinguishable from black holes (*e.g.* Chapter 33, [1]). However, there are good reasons to maintain the distinction between black stars and black holes. First, *quantum* analyses of gravitational collapse show that a black star evaporates in a finite time [2] and so it is impossible to take the infinite time limit. Second, theories of quantum gravity often predict that black holes have structure such as a string theory fuzzball [3] or a firewall [4]. Third, observations of the collision of two black objects can tell us if the objects are black holes or black stars and hence the distinction between these objects is experimentally meaningful [5]. The resolution of these issues has taken on a new urgency after the recent exciting observations by LIGO [6] and Fermi [7] in which gravitational wave emission from two coalescing black hole-like objects appears to have been followed by a gamma ray burst.

The essential idea behind equating black stars to black holes is that a collapsing star very quickly fades from an observer’s view, and there is no way to send in probes (*e.g.* light rays) at late times so as to see the surface of the black star. This idea is captured in the spacetime diagram shown in Fig. 1 where certain rays can hit the surface of the star but later rays arrive at the surface of the star after it has crossed into its own event horizon. So the surface of the black star can only be probed by rays that arrive sufficiently early. This is the usual interpretation, also described in [1], and if the object is probed at sufficiently late times, there is no way to send in probes to distinguish between a black star and a black hole.

The picture changes in a *quantum* analysis, since then a collapsing body produces a time-dependent metric that leads to quantum radiation and causes the body to slowly

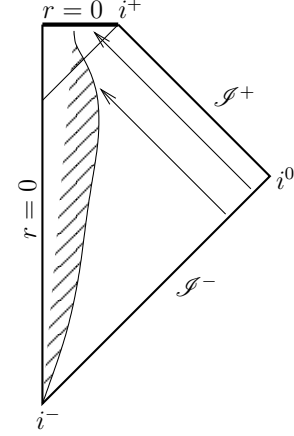


FIG. 1: Spacetime of a classical collapsing object (shaded region) that appears as a black star to an observer located near i^+ . Two null rays from \mathcal{J}^- are shown, one that collides with the black star and the other that does not.

evaporate even as it collapses [2]. This radiation, very similar to Hawking radiation from a black hole [8], does not require the event horizon of a black hole and holds for any collapsing body, even when it is outside its own Schwarzschild radius. Gravitational collapse leads to a black star that is continually collapsing and concurrently evaporating into quantum radiation. Then the collapsing object spacetime is shown in Fig. 2. Now every null ray that hits the collapsing object and reflects off of it will reach future null infinity \mathcal{J}^+ . This happens if the null ray collides with the collapsing object at any stage of the collapse. The only caveat is that the interaction of the null ray and the black star will lead to a time delay in the escape of the reflected ray but the amount of time delay will depend on when the reflection actually occurs.

In contrast to a black star, a “black hole” is a classical *vacuum* solution of Einstein’s equations and there is no matter distribution anywhere in spacetime except perhaps at the central singularity. Hence the collision of black holes will only lead to gravitational radiation because the spacetime is devoid of matter. On the other hand, black star collisions will lead to gravitational *and*

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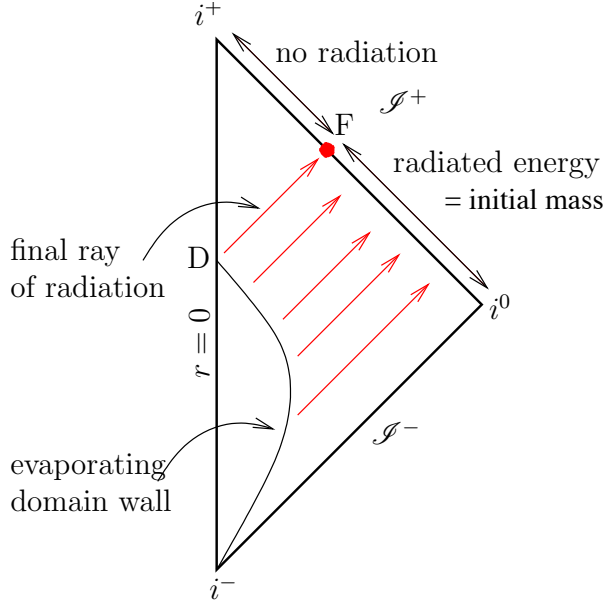


FIG. 2: Spacetime of a quantum collapsing object (labeled a “domain wall” in the figure) [2]. Now there is no event horizon and singularity, and all rays that hit the collapsing object reach \mathcal{J}^+ , even if they are delayed due to their interactions with the gravitational field.

electromagnetic radiation. Collisions of black stars can be a source of gamma ray bursts (*e.g.* [9, 10]), and such bursts will be preceded by gravitational wave emission whose characteristics are similar to those of black hole mergers. Thus, when two black stars collide, they can be distinguished from the collision of black holes by the presence of electromagnetic radiation.

In a realistic astrophysical setting the collision of two black holes might be accompanied by the collision of other accompanying matter, such as an accretion disk, around the black holes. Stellar mass black holes would have devoured surrounding matter and are therefore considered relatively clean environments, though new astrophysical scenarios might include such matter [11]. Even if there is surrounding matter that collides and produces gamma rays, this electromagnetic radiation and the gravitational radiation would be produced at the same time, with no specific time delay between them. On the other hand, the black star scenario clearly predicts a time delay between the gravitational wave emission and the gamma ray burst because first the metric outside the black stars coalesces and only then the material of the black stars coalesces.

We now estimate the energy radiated from the collision of two black stars each of mass M . The radius of each of the black stars is $R = 2GM$ and so the density is

$$\rho = \frac{1}{8G^3M^2} \sim 10^{14} \left(\frac{30M_\odot}{M} \right)^2 \text{ gms/cm}^3 \quad (1)$$

where $M_\odot \approx 2 \times 10^{33}$ gms is the solar mass. This density is high but still below the QCD density. Hence a $30M_\odot$ black star is mostly composed of ordinary protons and neutrons.

The collision of two black stars of mass M involves the collision of their constituent protons and neutrons which will lead to radiation of photons and other light particles. Since the gravitational binding between all constituents in this system is very strong, we treat the collision as being totally inelastic. Then the initial kinetic energy gets converted to radiation resulting in the release of total energy

$$E \sim Mv^2\delta \approx 4 \times 10^{49} \left(\frac{M}{30M_\odot} \right) \left(\frac{v}{0.5c} \right)^2 \left(\frac{\delta}{10^{-6}} \right) \text{ ergs} \quad (2)$$

where δ is the gravitational redshift of the energy as it escapes the collision region. The collision velocity will typically be an $O(1)$ fraction of the speed of light, and the gravitational redshift factor $\delta \ll 1$ will depend on how close the black star is to being a black hole.

We assume that the energy is released in a light crossing time $\sim R/c = 2GM/c \sim 3 \times 10^{-4}$ sec (for a $\sim 30M_\odot$ black star), which is the only relevant length scale in the problem. This time interval will be dilated by δ^{-1} and the emitted power in photons will be

$$P \sim 2 \times 10^{46} \left(\frac{v}{0.5c} \right)^2 \left(\frac{\delta}{10^{-6}} \right)^2 \text{ ergs/sec} \quad (3)$$

Note that the power is independent of the mass M . We can estimate the frequency of the photons by once again treating the collision as being totally inelastic. Then every proton in the black star gets stopped on collision and the emitted photon energy is simply the initial kinetic energy of the proton

$$E_\gamma \sim m_p v^2 \delta \approx 0.25 \left(\frac{v}{0.5c} \right)^2 \left(\frac{\delta}{10^{-6}} \right) \text{ keV} \quad (4)$$

Even though we cannot precisely estimate the event rate of black star collisions, we do know that the rate is lower for lower initial velocity since then the stars will take a long time to collide *i.e.* δ will be smaller. Then the emitted energy will redshift by a greater amount and there will be a greater time delay between the gravitational and electromagnetic emissions, making the gamma ray burst very faint and also temporally uncorrelated with the gravitational wave event. On the other hand, we expect that the number of black stars falls off with higher velocity. These two arguments suggest that there should be a velocity at which black star collisions peak. In terms of gamma ray bursts, it implies that the gamma ray bursts should have a typical photon energy. Further, the total power emitted should scale with this photon energy as seen by dividing Eq. (3) by (4),

$$\frac{P}{E_\gamma} \approx 10^{56} \left(\frac{\delta}{10^{-6}} \right) \text{ sec}^{-1} \quad (5)$$

This formula does not depend on the mass of the colliding black stars and neither on their velocities, and hence is an invariant of the model.

If an observed gamma ray burst is indeed due to colliding black stars, the burst should be preceded by gravitational wave radiation from the coalescing spacetimes of the black stars. The gravitational wave emission should be very similar to that calculated numerically for black hole collisions [12–14], and the final gravitational wave emission due to coalescence should be accompanied by the gamma ray burst when the material of the black stars coalesce. The waveforms of the emitted electromagnetic radiation will depend on the normal modes of the two black star system. Indeed, characteristics of the gravitational radiation preceding the gamma ray burst, together with the gamma ray burst, may allow us to infer the parameters of the colliding black stars and the initial conditions.

LIGO [6] has recently detected the gravitational wave signature from the merger of two black holes, each with

mass $\approx 30M_{\odot}$. This stunning announcement has been followed by a cautious but equally stunning claim by the Fermi collaboration [7] that they may have seen a gamma ray burst counterpart of the LIGO event. The energy and emission frequency of the gamma ray burst are broadly consistent with those estimated for black star collisions. If future gravitational wave events are followed by delayed gamma ray burst events, it would be strong support for the black star picture and would provide deep insight into gravitational collapse, black holes, and quantum gravity.

Acknowledgments

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